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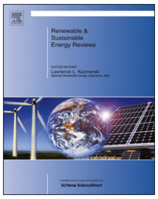

Demand response and smart grids—A survey

Pierluigi Siano*

Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II, 132, Fisciano (SA) 84084, Italy

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A B S T R A C T

The smart grid is conceived of as an electric grid that can deliver electricity in a controlled, smart way from points of generation to active consumers. Demand response (DR), by promoting the interaction and responsiveness of the customers, may offer a broad range of potential benefits on system operation and expansion and on market efficiency. Moreover, by improving the reliability of the power system and, in the long term, lowering peak demand, DR reduces overall plant and capital cost investments and postpones the need for network upgrades. In this paper a survey of DR potentials and benefits in smart grids is presented. Innovative enabling technologies and systems, such as smart meters, energy controllers, communication systems, decisive to facilitate the coordination of efficiency and DR in a smart grid, are described and discussed with reference to real industrial case studies and research projects.

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* Tel.: +39 0 89964294.
E-mail address: psiano@unisa.it

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1. Introduction

The smart grid (SG) is conceived as an electric grid able to deliver electricity in a controlled, smart way from points of generation to consumers that are considered as an integral part of the SG since they can modify their purchasing patterns and behavior according to the received information, incentives and disincentives [1–3]. As confirmed by some recent research [4,5], most of the advantages of SG are, in fact, due to its capability of improving reliability performance and customers' responsiveness and encouraging greater efficiency decisions by the customers and the utility provider. Accordingly, demand side management (DSM), including everything that is done on the demand side, represents an integral part of SG [6–9]. The complete integration of DSM requires communication systems and sensors, automated metering, intelligent devices and specialized processors. Smart metering and advanced information and communication technologies (ICT) solutions for energy management in buildings appear, in fact, as a tangible opportunity to achieve energy savings, exploit renewable energy resources (RES) and favor customers' participation in the energy market. New ICT infrastructures, supporting a more efficient network operation and allowing the communication of frequent price updates, offer new challenges for DSM. They allow a much more dynamic, reactive pricing mechanism required to take into account real-time availability of fluctuating RES [8–13] and to follow the evolution of the balance between supply and demand in real time. DSM commonly refers to programs implemented by utility companies to manage the energy consumption at the customer side of the meter [11,12]. Both utilities and customers can benefit of DSM programs that can help electricity power markets operate in a more efficient way [14], thereby reducing peak demand and spot price volatility [15,16].

A wide range of demand response (DR) programs and tariffs are already offered by utilities [13–28] that have been settled to use the available energy more efficiently and to encourage customer response and competitive energy retailers. These programs consist of conservation and energy efficiency programs, fuel substitution programs, demand response programs, and residential or commercial load management programs [12,29].

According to [30]: “Energy efficiency involves technology measures that produce the same or better levels of energy services (e.g., light, space conditioning, motor drive power, etc.) using less energy. The technologies that comprise efficiency measures are generally long-lasting and save energy across all times when the end-use equipment is in operation. Depending on the time of equipment use, energy efficiency measures can also produce significant reductions in peak demand”. According to this definition, energy-efficiency programs involve that, without modifying operating practice and, in order to reduce energy usage, new devices using less energy should replace existing consumers' devices. In order to push customers to acquire, install and adopt energy-efficiency measures in their facilities, energy-efficiency programs offer financial incentives and services. Different models for energy efficiency program administration exist that are generally administered by electric and gas utilities, state energy or regulatory agencies [31]. The most popular programs refund customers for installing energy-efficient equipment; however, other types of energy-efficiency programs exist.

Fig. 1 describes the potential impact of efficiency and DR measures on customer service levels. The opportunities and potential for both energy efficiency and DR depend on the customer's existing building and equipment infrastructure. The daily energy efficiency category of actions in Fig. 1 incorporates both short-term conservation actions and long-term investments in energy efficiency. End-use customers, in order to handle their electric service requirements and costs, can invest in energy efficiency or participate in a variety of DR activities such as signing up for a time of use (TOU) rate and shifting loads such as air conditioner or pool pump to off-peak hours. Some examples of DSM programs are real time pricing (RTP) and direct load control (DLC) programs. DLC programs for residential load management [18–20] are based on an agreement between the utility company and the customers. The utility, or an aggregator, can remotely control the operations and energy consumption of certain appliances such as lighting, thermal comfort equipment, refrigerators and pumps. An alternative to DLC is smart pricing, where users are encouraged to individually and voluntarily manage their loads, e.g., by reducing their consumption at peak hours [22–24]. In this regard, critical-peak pricing (CPP), time-of-use pricing (ToUP) and real-time pricing (RTP) are among the more popular options. According to RTP programs, the price of electricity varies at different hours of the day and each user is expected to individually respond to the time-differentiated prices by shifting its own load from the high-price hours to the low-price hours [26–28].

It is worth noting that effective DR behavior on shorter timescales requires additional investment to execute real-time or fast DR options (such as ancillary services or spinning reserves). Air conditioners or water heaters can be, for instance, integrated with demand-responsive controls in the basic electronics of the appliance to automatically provide day-ahead and real-time response capability. Key attributes and distinguishing features of various customer options include required frequency of response, underlying motivation and drivers, required customer actions, supporting infrastructure required to enable customers to participate and potential impact on the level of energy services [32,33].

2. Demand response

DR refers to “changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” [34,35]. DR, by promoting the interaction and responsiveness of the customers, determines short-term impacts on the electricity markets, leading to economic benefits for both the customers and the utility. Moreover, by improving the reliability of the power system and, in the long term, lowering peak demand, it reduces overall plant and capital cost investments and postpones the need for network upgrades [31,36].

The response in electric usage is handled through DR programs designed to coordinate electricity use with power system

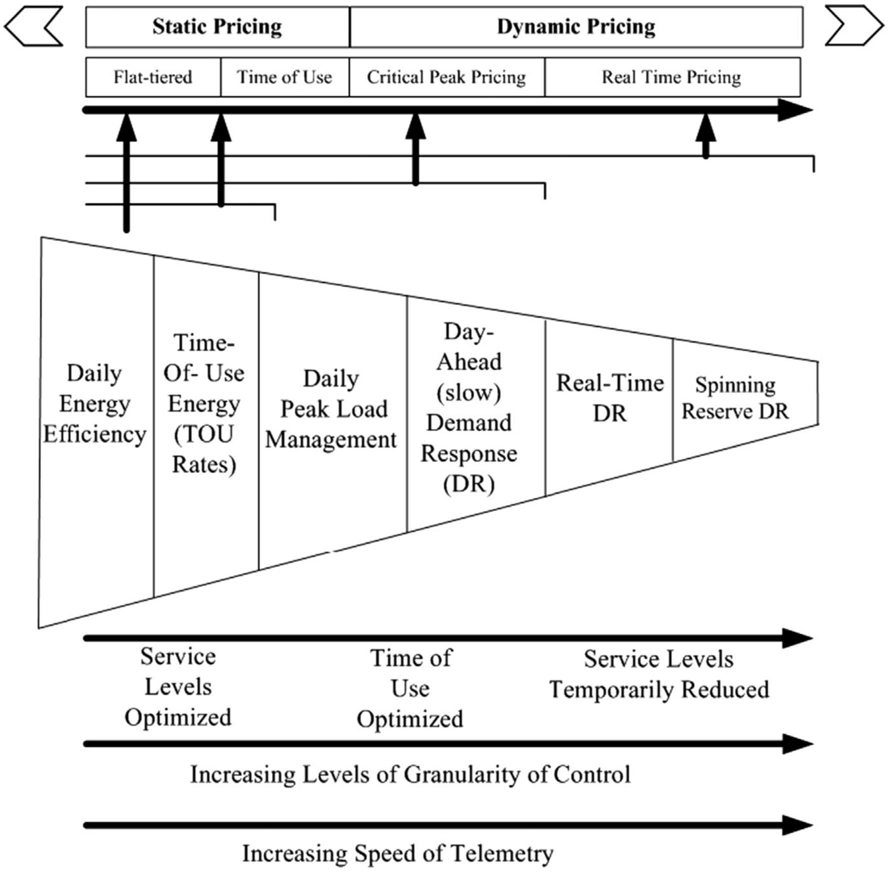

Fig. 1. Conceptual perspective of efficiency and demand response [34].

operation. DR is achieved through the application of a variety of DR resource types, including distributed generation, dispatchable load, storage and other resources that may contribute to modify the power supplied by the main grid. DR programs often use mechanisms to induce consumers to reduce demand in order to limit the peak demand; however, they may also support the demand increase during periods of high production and low demand. It is worth noting that, since DR may limit the consumers' comfort, these would desire limiting the time during which they may be exposed to such discomfort. Automation, monitoring and control technologies are, therefore, fundamental to manage energy-use process, making DR less hindering for the customer.

When customers participate in DR, there are three possible ways in which they can change their use of electricity [33,36]:

- reducing their energy consumption through load curtailment strategies;
- moving energy consumption to a different time period;
- using onsite standby generated energy, thus limiting their dependence on the main grid.

Load curtailment strategies can be attained, for example, by dimming lighting levels, decreasing the temperature set points of air conditioners, etc. Power consumption shifting may be, instead, achieved by commercial or residential customers by pre-cooling their facilities and shifting load from higher to lower cost time periods. Industrial facilities may also benefit from lower-cost off-peak energy by using storage technologies in order to postpone some production operations to an overnight shift, or by transferring their production to other industrial facilities in other service areas.

Customers can participate in DR programs directly with the utility, or through an intermediary. In the organized markets, such as wholesale electricity markets, the end-use customers are generally aggregated by intermediaries, known as curtailment service providers (CSPs), aggregators of retail customers (ARC) or demand response providers (DRPs), which present to the organized market the end-use customers' aggregated capability [35]. Retail customers may also be aggregated by the local distribution company that may present the related curtailments to the wholesale market. Moreover, if the users are provided with sufficient incentives, they can coordinate their usage to reduce the peak-to-average ratio in load demand or minimize the energy cost [17].

Owing to the recent advancements in SG technologies [37–40], the coordination between users may be automatic through two-way digital communication. An incentive-based energy consumption scheduling scheme for future SGs is proposed in [17], where the authors analyze a scenario where energy sources are shared between different customers, each one equipped with an automatic energy consumption scheduler, whose optimization objective is the minimization of the energy cost of the system. The scheduler functionality is deployed inside a given number of smart meters that are connected to both the power line and a communication network. The smart meters interaction is automatic and a distributed algorithm is run in order to determine the optimal energy consumption schedule for each user. The users are provided with the incentives to cooperate by using a simple pricing mechanism based on a game-theoretic analysis that allows overall system performance improvement. The optimal solution of a system-wide optimization problem is achieved by considering the pricing scheme and it corresponds to the Nash equilibrium of the energy consumption game between the participating users sharing the same energy sources [41]. It is worth noting that DR algorithms, representing the main requirements to enable the SG paradigm, can be realized as integrated functions of the distribution management system (DMS) at the network control center level.

2.1. *Customers' classification*

Two classes of entities, customers and DRPs, may interact with the utility/ISO for the purposes of DR according to the smart grid conceptual model of the National Institute of Standards and Technology (NIST) [42]. While customers are entities consuming energy and their participation in DR programs may be voluntary or mandatory, DRPs are intermediaries between the utility/ISO and the customers and provide a range of services related to DR.

In many cases, customers necessitate technical and financial support from the utility in order to install automated devices for DR that are able to automatically react to signals sent by utilities [43].

According to the amount of the consumption within their facilities, customers can be divided into the following classes [35]:

- large commercial and industrial (C&I);
- small commercial and industrial (C&I);
- residential;
- individual plug-in electric vehicles (PEVs); and
- fleet of PEVs.

Large C&I customers typically have within their facilities the most advanced technologies for controlling the loads (typically related to manufacturing and process control for industrial customers) and may, consequently, participate in either wholesale or retail electricity markets.

Inside commercial facilities, instead, the main loads are normally those used for the management of the facilities, such as heating, ventilation and air-conditioning (HVAC) systems and lighting. Most industrial customers and certain large commercial customers having on site generation equipment either for emergency backup or for auxiliary power may use this kind of generation for DR. Besides, some industrial facilities, such as pulp and paper manufacturing, have autonomous, discrete, production processes that, in case of necessity, can be shifted to other times of the day or to different days [43–45].

Residential customers are characterized by relatively small and somewhat limited types of loads and are not actually motivated to invest much in order to manage their electrical usage. They usually only take part in retail electricity markets and mainly participate in direct load control programs. This is likely to change in the near future, thanks to the deployment of new standards and technologies such as advanced metering infrastructure (AMI), which permits lower-cost equipment in the marketplace. New standards and technologies for building automation systems will also allow smart homes providing technical support to the SGs.

Small C&I customers are diverse and, in some cases, seem more like residential customers while in others cases look more like large C&I customers. PEVs represent an important new load on existing distribution systems and their diffusion will support load-shifting. Nevertheless, distribution systems should be correctly reinforced in order to avoid that their usage in DR programs may determine voltage problems, a degradation of the power quality and even probable damage to utility and consumer equipment [17].

2.2. *A conceptual model for the customers' domain*

The NIST Smart Grid Interoperability Standards [42] interim roadmap proposes a conceptual model for the SG, as shown in Fig. 2. The conceptual model is envisioned as an instrument that allows regulators at all levels evaluating the best strategies to achieve public policy goals that, along with business objectives, encourage investments in developing the nation's electric power system and building a clean energy economy [42]. NIST recommended this model from the perspectives of the different roles required in the SG. The model represents a reference for the various portions of the electric system where SG standardization works are scheduled. This conceptual model divides the SG into seven domains. Each domain and its sub-domains include SG actors and applications. Actors consist of devices, systems or programs that determine actions and exchange

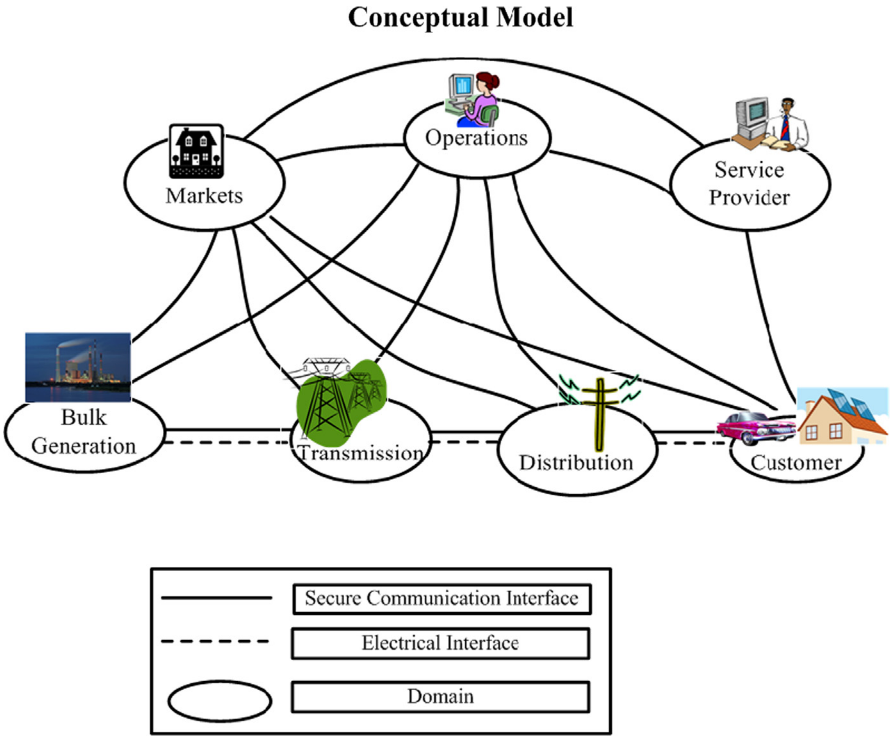

Fig. 2. Smart grid domains [2].

the information required for the realization of applications. Applications represent, instead, tasks that one or more actors within a domain have to achieve. While, for instance, smart meters, solar generators and control systems represent the actors, the corresponding applications may be home automation, solar energy generation, energy storage and energy management. More detailed descriptions may be found in the appendix of the NIST report [42].

Table 1 provides a modified view of the domains of SG in order to fully support DR business models. Actors in the customer domain enable customers to manage their energy usage and generation [2]. Some actors also provide control and information flow between the customer and the other domains. The utility meters along with further communication gateways such as a facility energy management system (EMS) are usually considered to be the boundaries of the customer domain. The customer domain is usually separated into sub-domains for home, commercial/building and industrial. The energy requests for these sub-domains are usually set at less than 20 kW of demand for home, 20–200 kW for commercial/building and over 200 kW for industrial [42]. Various actors and applications exist in each sub-domain; a meter actor and an EMS are always included in each sub-domain. The EMS represents the primary service interface to the customer domains and may be located either in the meter or in an independent gateway. The customer domain is electrically connected to the distribution domain and communicates with the distribution, operations, market and service provider domains. Advanced metering infrastructure (AMI) or other communications means, such as the Internet, allow the EMS to communicate with other domains. Home area network or another local area network is used by the EMS to communicate to devices within the customer premises. More than one EMS and, consequently, more than one communications path per customer may exist. The EMS represents the entry point for applications such as remote load control, in-home display of customer usage, reading of non-energy meters, monitoring and control of distributed generation, and integration with building management systems and the enterprise. The EMS may provide auditing/logging for cyber security purposes. Some actors also provide control and information flow between the customer and the other domains, as shown in Fig. 3.

2.3. Demand response programs

In order to motivate customers, DR programs should increase customers' understanding of the benefits deriving from DR and improve their capability to take part in DR programs using control technologies, such as smart thermostats and energy information. The main reasons for encouraging customers to participate in DR programs vary from monetary savings, to the aspiration to help avoiding blackouts, to a sense of responsibility. On the other end, several concerns and uncertainties discourage customers from participating in DR programs. These are mainly due to the uncertainty of price response programs, the undefined quantity of load that might be available for reduction during an event, the economic viability of participating in a DR program and the willingness to maintain occupant comfort during a DR event. However, utilities can tackle most of these concerns through smart program design, coordinated support and by allowing customers taking part in more than one program. Utilities should, moreover, offer an integrated set of coordinated services to encourage customers through different stages of program participation and technology adoption. They should be responsible for enabling technologies and offer financial and mediation assistance, such as locating and employing contractors. In particular, as small and medium customers may not have established relationships with vendors, they will decide to take part only if utilities work with them on designing and executing DR programs. There are many types of DR programs that can be classified according to various criteria; Table 2 summarizes some classifications proposed in the literature [46].

Even if different classifications of DR can be found in the literature [47], DR programs can be roughly classified into three groups according to the party that initiates the demand reduction action [31,36], as also shown in Table 2.

(1) Rate-based or price DR programs: in this program type, DR is implemented through approved utility tariffs or contractual appointments in deregulated markets according to which the price of electricity varies over time in order to motivate customers to adjust their consumption patterns. The price of electricity may be different at pre-set times or may vary dynamically according to the day, week and year and the existing reserve margin. Customers would pay the highest prices during peak hours and the lowest prices during off-peak hours. The prices can be established a day in advance on a daily or hourly basis or in real time and the customer would react to the fluctuations in the electricity prices. Examples of programs in this category are shown in Table 3. Many utilities offer some type of price-based DR tariffs to customers; however, price-based DR accounts for just a minor part of the total existing DR programs.

(2) Incentive or event-based DR programs: this category of DR programs rewards customers for reducing their electric loads upon request or for giving the program administrator some level of control over the customer's electricity-using equipment. A set of demand reduction signals, in the form of voluntary demand reduction requests or mandatory commands, is sent by the utility or the DR service provider (aggregator) to the participating customers. Incentive or event-driven DR can be invoked in response to a variety of trigger conditions, including local or regional grid congestion, system economics, or operational reliability requirements, local or system temperature [31,36]. Examples of programs in this category [48–54] are shown in Table 3. In cases of

Table 1
Domains of smart grid in order to fully support DR business models.

Domain name	Domain description
Customers	Any entity that takes gas and/or electric service for its own consumption. The consumers of electric power. Customers include small to large size C&I customers and residential customers
Markets	Power market is a system for effecting the purchase and sale of electricity, using supply and demand to set the price
Service providers	An entity that provides electric services to a retail or end-use customer
Operations	The management of generation, market, transmission, distribution and usage of the electric power
Generation	The production of bulk electric power for industrial, residential and rural use. It also includes power storage and distributed energy resources
Transmission	Electric power transmission is the bulk transfer of electrical energy, a process in the delivery of electricity to consumers
Distribution	Electricity distribution is the final stage in the delivery of electricity to end users. A distribution system's network carries electricity from the transmission system and delivers it to consumers
Microgrid	The local grid for distributed energy resources management and delivery

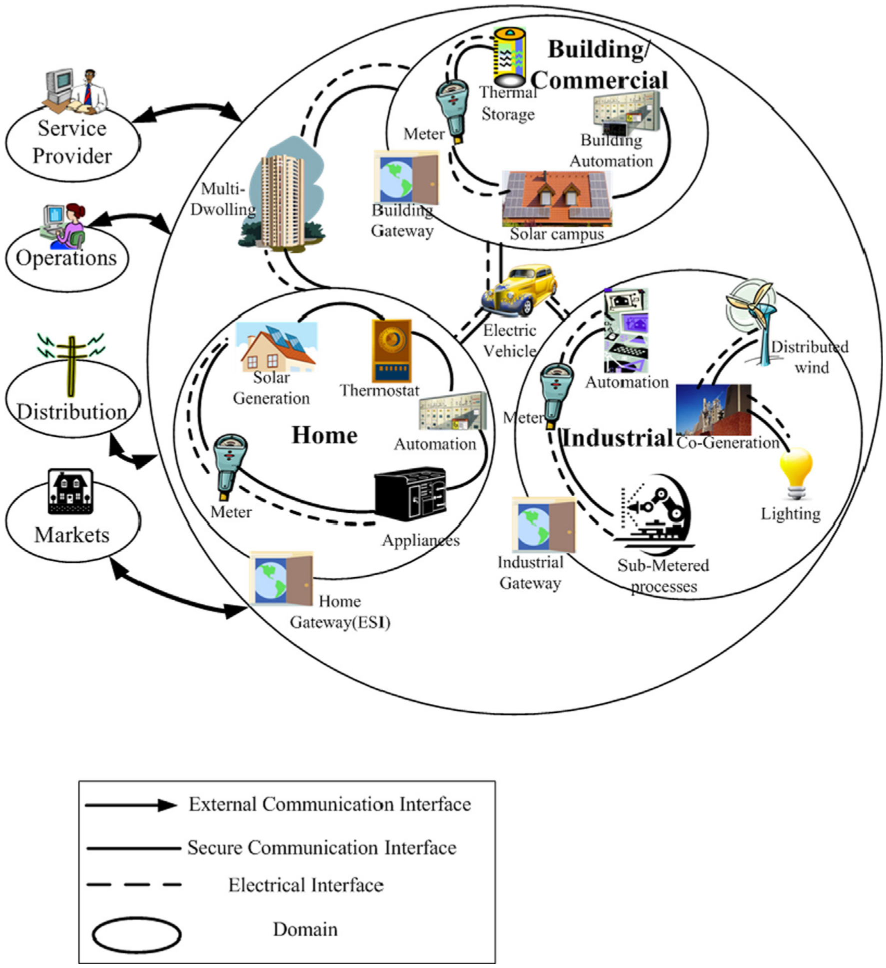

Fig. 3. Overview of the customer domain [2].

Table 2
Classification of demand response programs [50].

Classification criteria	Dualities	
Purpose	Reliability	Economics
Trigger factor	Emergency-based	Price-based
Origin of signal	System-led	Market-led
Type of signal	Load response	Price response
Motivation method	Incentive-based	Time-based rates
Control	Direct load control	Passive load control
System/market structure	Vertically-integrated regulated system	Liberalized market
Promotion and financing	By regulator	By market agents
Targeted customers	High-voltage (industrial and large commercial)	Low-voltage (small commercial and domestic)
Automation of response	Manual response (without enabling technologies)	Automatic response (with AMI and/or other smart devices)

incentive- or event-based DR programs, upper limits on the duration of individual events and the total number of event-hours per year are fixed: in some cases programs are assumed to be used no more than 40–100 h per year [51]. These limits are mainly due to both the limitations of the customer availability and current DR technologies.

(3) Demand reduction bids: customers participating in this category of programs initiate and send demand reduction bids to the utility or the aggregator [36]. The bids would normally consist of the available demand reduction capacity and the requested price. This program mainly stimulates large customers to deliver load reductions at prices for which they are willing to be curtailed, or to recognize the load quantity they would be willing to curtail at the announced price [50]. Within these broad categories of DR programs there are several different program types [31] as shown in Table 3.

An alternative way to look at the various DR programs is to distinguish between [47] market DR (i.e., real-time pricing, price signals and incentives) and physical DR (i.e., grid management and emergency signals). While market DR, is activated by economics, physical DR depends on reliability requirements. DR aiming to improve system reliability is generally implemented through emergency-based, system-led, load-response, incentive-based, direct-load control programs. On the other hand, DR aiming at reducing system costs is generally implemented through price-based, market-led, price-response (using time-based rates) and passive load control programs.

Table 3
Common types of demand response programs [33].

Price options	Incentive- or event-based options	Demand reduction bids
TOU (time of use rates): rates with fixed price blocks that differ by time of day	Direct load control: customers receive incentive payments for allowing the utility a degree of control over certain equipment	Demand bidding/buyback programs: Customers offer bids to curtail load when wholesale market prices are high
CPP (critical peak pricing): rates that include a pre-specified, extra-high rate that is triggered by the utility and is in effect for a limited number of hours	Emergency demand response programs: customers receive incentive payments for load reductions when needed to ensure reliability	
RTP (real-time pricing): rates that vary continually (typically hourly) in response to wholesale market prices	Capacity market programs: customers receive incentive payments for providing load reductions as substitutes for system capacity	
	Interruptible/curtailable: customers receive a discounted rate for agreeing to reduce load on request	
	Ancillary services market programs: customers receive payments from a grid operator for committing to curtail load when needed to support operation of the electric grid (i.e., ancillary services)	

Table 4
Potential benefits of demand response [50].

	Operation	Expansion	Market
Transmission and distribution	Relieve congestion manage contingencies, avoiding outages Reduce overall losses Facilitate technical operation	Defer investment in network reinforcement or increase long-term network reliability	
Generation	Reduce energy generation in peak times: reduce cost of energy and possibly emissions Facilitate balance of supply and demand (especially important with intermittent generation) Reduce operating reserves requirements or increase short-term reliability of supply	Avoid investment in peaking units Reduce capacity reserves requirements or increase long-term reliability of supply Allow more penetration of intermittent renewable sources	
Retailing			Reduce risk of imbalances Reduce price volatility New products, more consumer choice
Demand	Consumers more aware of cost and consumption, and even environmental impacts Give consumers options to maximize their utility: opportunity to reduce electricity bills or receive payments	Take investment decisions with greater awareness of consumption and cost	Increase demand elasticity

3. Potential benefits of demand response in a smart grid

Depending on the target, design and performance, as well as on other factors, such as the utilized enabling technologies and the structure of the system, DR may offer a broad range of potential benefits on system operation and expansion and on market efficiency [34,43,46]. The benefits of DR can be classified in terms of whether they accrue directly to participants or to some or all groups of electricity consumers as follows:

- Participant bill savings: electricity bill savings and incentive payments the customer receives for agreeing to modify load in response to current supply costs or other incentives.
- Bills savings for other customers: lower wholesale market prices that result from using less energy when prices are high, or from shifting usage to lower-priced hours.
- Reliability benefits: refer to customers' benefits perceived from reduced probability of being involuntarily curtailed and incurring even higher financial costs and inconvenience, or to societal benefits according to which the customer is gratified from helping avoiding extensive shortages.
- Market performance: DR prevents the exercise of market power by electric power producers.
- Improved choice: customers have more options for electricity costs management.
- System security: system operators are endowed with more flexible means to meet contingencies.

These benefits can be also categorized according to the activity of power systems where they originate [46] as shown in Table 4 and described in the following.

3.1. System operation

DR programs, where customers can react to price signals fairly reflecting real operational costs of generation and network, can attain relevant savings in system operation. A portion of the demand in times of high generation costs may be, for instance, avoided or shifted to less-expensive periods. Thanks to DR programs, system operators and distribution utilities can take advantage from avoided generation costs as well as deferred transmission and distribution costs. In case of generation or distribution outages, DR that is dispatched by the system operator on short notice can help the electric system to return to the pre-contingency levels by reducing electricity demand at critical times [43]. DR, by facilitating the real-time balance of supply and demand, is also considered as a main option to mitigate the problems caused by the variable and uncertain output of intermittent RES [55,56]. The contribution of DR to real-time balancing and to the compensation of supply unavailability in case of generation outages may involve a reduction in the requirements of operating reserves for a certain level of short-term reliability of supply [57]. Moreover, DR can contribute to reduced lines losses [58] and help relieve network constraints or avoid outages in case of contingencies [59]. DR programs can also deliver ancillary services for network system operators, such as voltage support, active and reactive power balance, frequency regulation and power factor correction [60]. The upper end of the DSM spectrum is represented by spinning reserves (SR) implemented by loads [47]. Loads may, in fact, act as a virtual (or negative) spinning reserve if their power consumption is associated in a smart way with the grid state (i.e., a droop control). In its simplest way, if frequency drops, the devices absorb less power. Moreover, loads, controlled from a central dispatch and management node, and modern SCADA standards like IEC 61850 [61], may also behave as a virtual storage via load shifting. The aggregation of many of such loads leads to sizes that can participate in power markets and compete with traditional electric storage systems [65]. All these effects on networks can mean an increase in network reliability and quality of supply.

3.2. *Market efficiency*

It is widely recognized that a more active participation in the market by the demand side could have significant benefits. In particular [62–67]

- consumers may reduce their energy cost by shifting their load from periods of high prices to periods of lower prices;
- the aggregated load profile is flattened by the shifting of demand and hence the overall cost of producing electrical energy is reduced;
- if this reduction in cost translates into a reduction in prices, also consumers who do not alter their demand in response to prices may benefit;
- the capability of generating companies to exercise market power is mitigated.

A significant enhancement in market efficiency may be achieved in liberalized environments, thanks to market-driven DR programs. These programs are normally carried out in the form of time-varying tariffs and allow an active participation of the demand side in the market. DR may, in fact, decrease wholesale market prices for all the traded energy in the market. Price responsiveness during periods of lack of generated power and high wholesale prices allows mitigating high wholesale and retail prices and their volatility [68] and the effects of extreme system events [69]. By adjusting their demand in response to price signals, consumers can maximize their utility by consuming electricity proportionally to its cost at a certain time [70]. The amount of savings from lowered wholesale market prices is determined by the amount of energy traded in the markets. Other short-term benefits include avoided variable supply costs when customers are served by vertically integrated utilities. The flattening of the demand profile also implies price reductions [71], which denote wealth transfers from generators to consumers and not real savings for the society as a whole [72]. The improved elasticity of demand also allows limiting the extent and number of price spikes and easing the generators' ability to exercise market power in wholesale electricity markets [71–74]. In organized markets, during periods of high demand and insufficient supply, more expensive generation is, in fact, dispatched, thus determining an increase in market clearing prices to high levels. Price-response mechanisms allows a decrease in demand when market clearing prices increase, thus avoiding the potential for the supplier to exercise market power, increasing the number of suppliers in the market, reducing concentration and making collusion more difficult. DR may also allow utilities, retailers and customers to hedge their risk exposure to price volatility and system emergencies. Conversely, a more elastic demand will mostly decrease the profits of the generating companies [75,76]. Adequate amounts of price-responsive demand may also avoid using price caps and other market mechanisms such as installed capacity markets.

3.3. *System expansion*

As already stated, DR can potentially modify the pattern of customer loads, which may result in a shift in the mix of peak versus base-load capacity. DR can also reduce both local peaks, in a particular area, and system peaks, therefore displacing the need to build additional generation, transmission, or distribution capacity infrastructure [43]. Since at the local level, electrical networks are dimensioned for the peak expected demand, the reduction of local peaks allows, in fact, avoiding network reinforcement for an assigned level of reliability or increasing, in the long-term, network reliability. On the other end, at the system level the smoothing of the demand pattern implies deferring the installation of new capacity in peaking units and postponing new investments in capacity reserves [72,77] for an assigned level of reliability or increasing, in the long-term, network reliability.

4. Enabling smart technologies for demand response

The availability and the advances of innovative enabling technologies may provide many power system and societal benefits and highly increase those attainable with existing DR programs [78–84]. Developments in integrated electronic circuits, control systems, and information and communications technologies have, in fact, significantly improved the functionality of advanced metering and DR technologies [43]. The combination and interaction of some key elements, such as building infrastructure, enabling technologies (e.g., building electro-mechanical systems, appliances), and customer behavior determine the capability and prospective for energy efficiency and DR at a customer's facility [31]. In particular, innovative enabling technologies and systems integration are decisive to facilitate greater coordination of efficiency and DR [85]. Enabling technologies consist of, but are not limited, to the following ones:

- demand-reduction strategies optimized to meet different objective functions both related to energy price or to emergency events;
- two-way communications interval meters that allow customer utility bills revealing the actual energy usage pattern;
- communication devices used to inform customers of load curtailment actions;
- energy-information tools that allow accessing to load data in near-real-time, evaluating load curtailment performance relative to the baseline usage, and informing facility operators on potential loads to consider for curtailment;
- load controllers and building energy management control systems for DR optimization, that are also conceived in order to enable automation of load curtailment strategies;

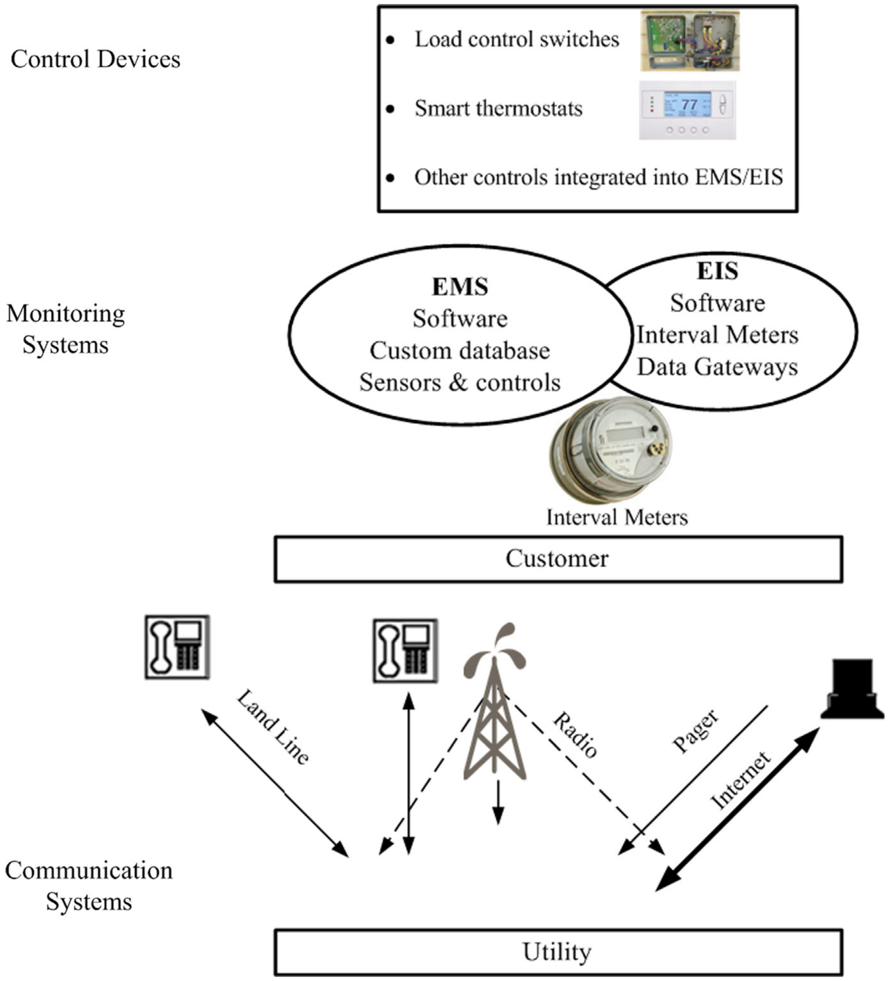

Fig. 4. Categories of DR Technologies.

- on-site generation equipment used either for emergency backup or to meet primary power needs of a facility.

Some innovative smart technologies, such as smart meters, used to record energy usage on a more frequent basis and smart thermostats, that automatically regulate room temperatures according to price changes or remote signals from system operators, represent a key requirement for most DR programs and allow increasing the amount of load that could be reduced under a DR program [43]. These innovative enabling technologies permit both better customer receptiveness and greater utility confidence.

Automated response technologies, enabling both enhanced and remote control of the energy consumption and peak load can be divided into three general categories: control devices, monitoring systems, and communication systems as described in the following sections and shown in Fig. 4.

5. Control devices for demand response

Load control devices are both stand-alone and integrated into an EMS for large facilities and consist of technologies such as load control switches and smart thermostats. Load control switches are used for remote control of specific end-use loads such as compressors or motors and are connected to the utility by means of communications systems. Smart thermostats are remotely controlled by the utility and/or the customer and allow programming of variations in temperature settings with a softer control instead of using on-off switching devices. Some smart thermostat models now may operate like small-scale, limited-purpose versions of a building automation system as they act similar to a repeater and provide reliability, price and event signals to other appliances and loads.

5.1. Smart technologies for building and home energy management

The interaction between customers and distribution networks can be provided by means of active DR systems that are also located within homes. These devices include both simple devices and local EMSs for achieving both energy management and bi-directional communication with energy distributors and retailers. EMSs, by receiving market and system signals, can manage loads, heating, ventilation and air conditioning (HVAC) systems, storages and local generation units, according to user preferences. These smart technologies allow achieving different functions such as automatic reduction of the energy consumption as a result of high energy process or an emergency signal received from the distribution company. Other important functions are related to electric and heating management: the EMS may decide to use only gas heating, heat pumps, or both of them, depending on gas and electricity prices, external and desired temperatures for each room, and current heat pump coefficient of performance (COP). HVAC and lighting are the usual targets of an appealing DR strategy as they are coincident with utility system peak loads (both in summer and winter) and represent the two main loads of a commercial facility, if compared to the total building energy consumption. Moreover, HVAC and lighting controls are predominant and proven solutions and a wide range of facilities and applications already exist. For utilities, whose annual peak occurs in the summer, commercial cooling and lighting most significantly contribute to that summer peak. For winter peaking utilities, lighting and electric heating are the prime end-use contributors. Moreover, as small modifications of the energy consumption of HVAC and lighting do not critically effect their operations, they are also easy targets for energy curtailment. For example, it is possible to raise or lower the temperature set-points of HVAC of a few degrees and for a limited time with negligible impact on comfort.

Miscellaneous loads, such as refrigeration equipment, elevators, outdoor signage, and plug loads may be also, in many cases, turned off without a critical impact on their normal operations. Embedded controls also enable customers to automatically shift or defer operations and to modify settings of selected appliances with integrated electronics in order to take advantage of low-price periods. Customers may also program smart appliance, such as innovative washing machines, water heaters, dryers, dishwashers, refrigerators, in order to automatically respond to price, reliability, and other DR event signals.

5.2. Applications of smart technologies for building and home energy management

Several research projects have been carried out during the last years with the objective to assess the benefits of smart technologies for building and home energy management and these technologies have been already applied in real cases. An autonomous demand side energy management system, based on a smart grid communication infrastructure is proposed in [11] with the objective to minimize the electricity cost for users. A decision-support tool allowing residential consumers optimizing electrical energy services acquisition is proposed in [29]. An algorithm for the automatic schedule of thermostatically controlled loads according to both household comfort settings and price and consumption forecasts is presented in [86]. A three-step control method for the optimal management of domestic technologies able to preserve the residents' comfort is presented in [87]. The method allows the cooperation between distributed generation, distributed storage and demand side load management. A platform able to develop consumer-based demand side management and estimate the advantages deriving from optimal appliance selection and resource management test is proposed in [88]. Residential energy hubs, combined into an automated decision making technology for smart grids, are presented in [89]. All major residential energy loads, storage and production components can be optimally controlled by the proposed residential energy hubs while properly considering the customer's preferences and comfort level. A framework for the optimal scheduling of household appliance operations according to electricity payment minimization and waiting time reduction is presented in [90]. A methodology able to assess load management programs and to select the best alternative is proposed in [91]. A novel load management technique for the air conditioner loads in large residential apartments is presented in [92]. Effective and convenient load management measures for both customers and distribution operators can be achieved by using the proposed technique, based on Markov processes. A load commitment framework allowing minimizing household payment by automatically shifting responsive electrical loads, including battery storage and plug-in hybrid electric vehicles (PHEVs), is proposed in [93]. A simulation environment for the assessment of DR algorithms is presented in [94]. An innovative decision support and energy management system (DSEMS) for an efficient use of energy, especially in a residential environment, is proposed in [95,96]. The proposed DSEMS, realized in the framework of an industrial research project leaded by BTicino, receives as inputs, the values of available energy resources and some information such as those received from the distribution network operator (DNO) or from the customer or those related to the environmental parameters. The command signals used for the management of thermal and electrical loads and the messages for the end user represent its outputs as shown in Fig. 5. The following climate control systems have been implemented in both summer and winter seasons:

- during the economic tariff period when the power consumption exceeds the power limit, the temperature set point of the split is gradually changed in order to reduce the electrical power absorption;
- during the expensive tariff period in addition to the previous control, the system also modifies the temperature set point of the split in order to reduce the power absorption.

The DSEMS allows reducing energy costs while preserving the user comfort, moreover it may also contribute to the alleviation of distribution networks constraints in case of peak loads due, for example, to air conditioners usage during summer that may cause load interruptions.

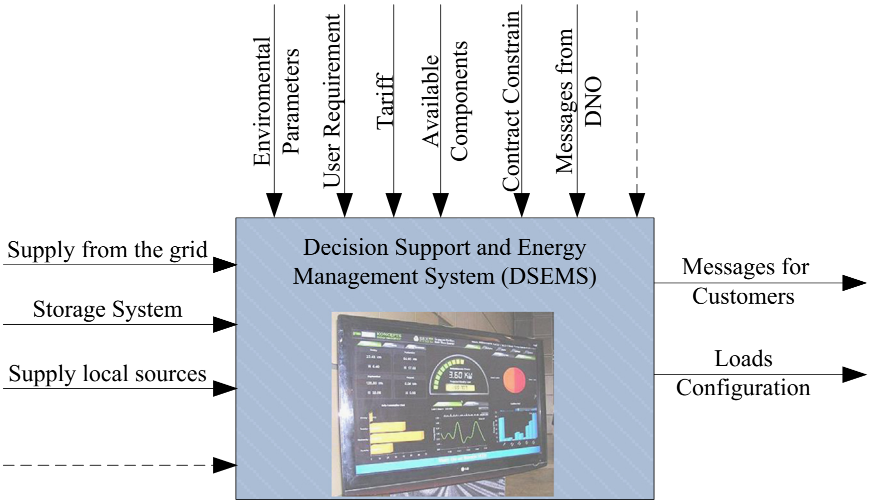

Fig. 5. Decision support and energy management system.

5.3. Backup generators and energy storages for industrial and commercial customers

By using backup generators, industrial and commercial customers may employ a simple and suitable scheme to shed load from the grid in exchange for utility payment. They may, in fact, gain additional economic value from their equipment while maintaining their normal operations. Pollutant emissions represents, however, a big problem when using backup generators for DR. Due to limited emissions permits, mainly for emergency backup generators, backup generators operation is only allowed for a limited number of hours per year [97]. In some other cases, local generation management is also possible thanks to some appliances, such as dishwasher and washing machine that, in favorable generation conditions, allows achieving a kind of local dispatching. This strategy, according to which the management of all local resources is optimized, may be easily adapted also in the tertiary sector or in smart buildings. Smart building, even if usually separated, may, indeed operate in a coordinated manner in order to offer further functions and services, both for the building itself and for the distribution electrical system.

Energy storage units may be also included in the house and building energy management in order to increase load management related functions and security levels for some critical applications. Moreover, surplus power from local generation may be used for charging PEVs and employed in emergency or high price situations.

6. Monitoring systems

Monitoring systems consist of smart meters, AMI, EMSs, and energy information systems.

6.1. Smart metering

Directive 2009/72/EC requiring European Member States to proceed with the roll-out of at least 80% (i.e., around 250 million) of smart meters in their territory by 2020 favoured the deployment of smart metering systems in Europe [98]. In most cases, smart metering installations are led by DSOs/utilities and are part of a wider smart grid project, typically combined with innovative automation and control systems on the grid side or with DR and energy management applications in the smart home (e.g., Smart City Malaga, Grid4EU, Inovgrid, Low Carbon London, Price) [99].

Smart-meter systems comprise an electronic box and a communications link. A smart meter measures electronically customer consumption, and possibly other parameters, in a certain time-interval, and transmits measurements over a communication network to the utility or other actor responsible for metering. This information can be shared with end-use devices informing the customers about their energy consumption and related costs. Smart-meter types are distinguished according to the combination of some features such as the data-storage capability of the meter, the communication type (i.e., one-way or two-way), the connection with the energy supplier [100]. In most countries there are no suitable requirements for functionality of smart meters, however some examples of common minimum requirements for smart meter functionality can be found in [101,102]. In most cases, the electricity provider's tariff and rate designs determine requirements such as the duration of meter intervals or the time resolution (generally ranging from 15 min to 1 h) according to which both the consumption and production of active and possibly reactive power should be separately measured. As missing or erroneous data may determine substantial costs, data must be reliable and accurate. The accuracy requirements of static billing meters are defined in IEC 61036 standards in order to preserve the accuracy of the measurement data. Meter data can be stored in the meter for days or weeks before it is transferred to the utility's meter data management system. Compensations for some power quality deficiencies can be also considered; therefore the future meters should be also register some basic power quality characteristics [100].

In order to implement dynamic rates and DR, an increasing number of projects are testing the installation of smart meters, home energy controllers, smart appliances and in-home displays. Smart meters are, usually, required for price-response and large commercial DR programs in order to measure and record the energy consumption at intervals ranging from 15 to 60 min and generally exist within a broader infrastructure which is often called AMI, including new functionalities and advances services.

6.2. Advanced metering infrastructure

An AMI is different from traditional automated meter reading (AMR) and automatic meter management (AMM) as the latter may be considered subsystems of an AMI, when considering the complexity of the communication network and protocols. An AMI network consists of a number of integrated technologies and applications including smart meters, wide-area networks (WAN), home (local) area networks (HANs), meter data management systems (MDMS), operational gateways and systems for data integration into software application platforms, neighborhood area networks (NANs), as shown in Fig. 6. AMI denotes a system that, on request or on a pre-defined schedule, measures, saves and analyses energy usage, receiving information from devices such as electricity meters using various communication media [103].

At the consumer level, smart meters communicate data to both the user and the service provider and the HAN automatically collects data from metering devices like water, gas, heat, electricity. NANs are networks used for meter data collection. These data are transferred to a central database and used for various purposes. The service provider (utility) employs systems that collect and analyze logged data to optimize operations, energy costs and consumer service. An immediate feedback on consumer outages and power quality can be, for instance, provided and grid automation may be also supported by AMI's bidirectional communications infrastructure [104].

A HAN allows connecting smart meters to controllable electrical devices and implementing energy management functions by using devices such as programmable communicating thermostats and other load-control devices, in-home displays, PEVs, and distributed power-generation devices. It also may offer a smart interface to the market and support security monitoring.

A MDMS is a database performing validation, editing and estimation on the AMI data in order to guarantee that the data are accurate and complete. It is also endowed with analytical tools that enable the cooperation with other information systems (operational gateways) thanks to which AMI can also support advanced management systems such as: distribution management system with advanced sensors, advanced distribution and transmission operations, advanced outage management, Distributed Energy Resources (DER) operation, distribution automation, distribution geographic information system, advanced asset management [104].

6.3. Energy management systems

EMSs allow monitoring, analyzing and controlling building systems and equipment by means of a series of sensors, switches, controls and algorithms.

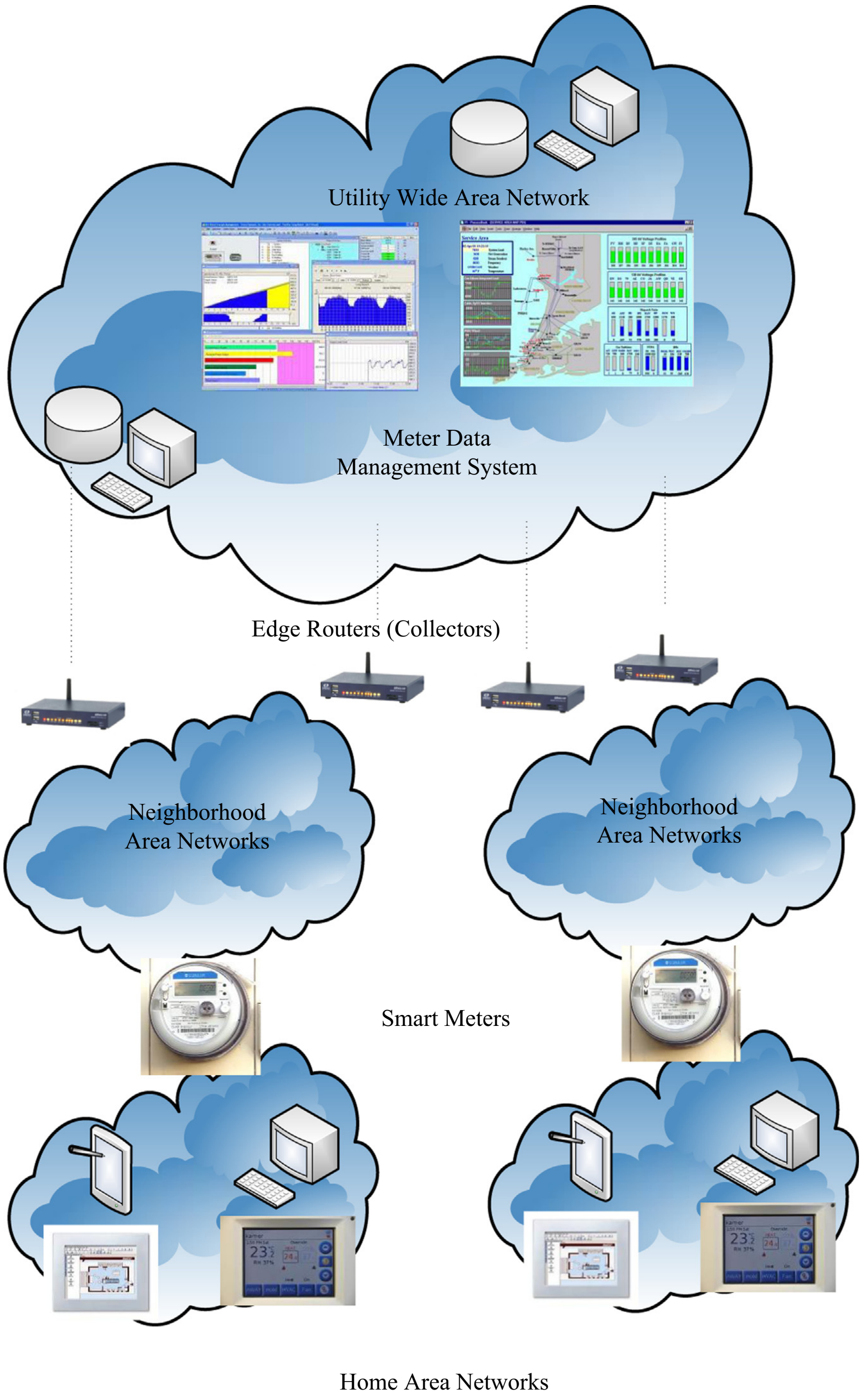

Fig. 6. AMI system.

Monitoring individual loads and appliances is required for load control strategies, verification of control response and development and updating of load models. Some type of load control strategies, generally developed for residential customers, may require, in fact, individual monitoring capabilities. In these cases, the deployment of an appropriate infrastructure within end user's facilities is required in order to communicate the information from individual appliances to the control center.

An EMS is essentially designed to improve building energy performance by saving energy and/or reducing peak demand, however it may also carry out automated DR functions. If the measurements are used in control loops or observed online a time resolution of about 1 min is usually needed and long delays are undesirable. Conversely, a higher time resolution is typically adequate for modeling and verification purposes even if a faster response of 1–10 min makes these tasks more efficient.

Centralized control of multiple buildings on a campus or geographically dispersed facilities may be achieved by installing an EMS. Moreover, several national chain retail stores employ EMSs in order to aggregate small and medium sized commercial facilities for DR inside a utility's service region.

6.4. *Energy information systems*

Energy information systems (or EIS) may operate as the gateway for two-way communication between a utility and existing

EMS or run independently from an EMS. Like EMSs, facilities install EIS systems mainly for energy information and load management instead of for use in playing a part in DR. They are mainly used in order to gather data and make available information related to the system performances to end users and utilities. However, if endowed with automated response capabilities, they can also offer notification capabilities for end users. These further capabilities, mainly based on monitoring and recording real time energy use data for analysis of building operations, billing analysis and reporting, allow receiving alerts concerning DR events or providing both notification and analysis capability. Moreover, they may also allow automated response to utility-requested events or support in order to detect errors, to analyze the effects of operational changes made in response to an event and to make decisions.

7. Communications systems

Communications systems are required for implementing DR programs: market and emergency signals may be delivered by means of the metering infrastructure or other one-way or two-way communication systems (telephone, radio media, or wireless paging technologies, Internet, GSM etc.) between a utility and customers. One-way communicating devices, extremely cost effective and simple to use, are used by utilities to alert program applicants and/or the appliance directly about a DR event. However, they do not allow monitoring and verification of the DR impact with accurate precision. Two-way communicating devices, even if more expensive than one-way control devices, due to higher upfront costs, permit, instead, utilities to get reply confirmations from customers and, in the case of smart meters, to automatically send measured event load response to utilities. Two-way communication control technology is the most appropriate as it also allows monitoring the number of facilities available at the time of a DR event and identifying the level of load diversity. By using such a kind of technology, more accurate monitoring and verification of the DR impact is possible as the utility may also directly measure every customer's load reduction involvement during an event in near real time. This also enables an easier settlement of billing or program incentive payments. Moreover, two-way communication control technology also allows the utility managing intermittent generation by using DR combined with other resources in order to furnish ancillary services such as spinning reserve, frequency control, and voltage support. Two-way communication also offers supplementary benefits for customers, in particular higher consuming customers may achieve a greater load shed per event thanks to more sophisticated two-way technology and facility managers may preserve acceptable operating ranges for equipment or cope with multiple facilities. Accordingly, the smart grid communication architecture consisting of two-way communicating devices with the central SG controller, exhibits a hierarchical structure as shown in Fig. 6. It includes HANs that comprise appliances and devices within a home and connect the smart meters with the communications gateway, NANs that gather data from multiple HANs and deliver the data concentrator unit (DCU), WAN that transmits metering data to central control centers and, finally, a gateway collecting information from the HAN members and communicating these data to interested parties [105]. Different communication technologies and requirements could be employed to realize the above networks and a deep analysis of communication requirements and capabilities of the different type of network is described in [106]. However the most common communication choice is the combined use of PLC for the smart meter-concentrator connection in the secondary substation and the use of GSM/GPRS for the concentrator-MDMS connection [100].

In the following an outline of the potential proper technologies for smart metering is given by distinguishing between wired and wireless systems. It is worth noting that, in order to implement an architecture characterized by high-speed, expandable, and "peer-to-peer" that can be used with DERs and power distribution networks, both wireless and wired communication technology should accomplish to IEC 61850 [107].

The integration of increasing numbers of intelligent electronic devices (IED), applications and exchanging between multiple companies has determined, in fact, the requirement of new network architectures able to analyze, store, integrate and process the increasing quantity of information available in the various devices and the necessity of a common format that covers all the areas of data exchange in the electrical power domain.

The standard for the exchange of information of the distribution networks is based on Common Information Model (CIM) and defines a control architecture, that can deal with the complexity of smart grids, and a bus of information, accessible to the different control functions, that can exchange the information related to the state of the system on the basis of a common format.

7.1. *Wireless communication systems*

Wireless architecture can be either an option for HANs, NANs and WANs, or obligatory in case of vehicle-to-grid (V2G) communications, and various communication technology and standards could coexists in different part of the smart grid. IEEE 802.15.4 (ZigBee) and IEEE 802.11 (Wi-Fi) are appropriate technologies for smart meters in HANs and NANs, where the coverage range varies from tens to hundreds of meters [105]. The coverage requirements (of tens of kilometers) for WANs impose the use of cellular wireless networks like GPRS, UMTS, LTE, or broadband wireless access networks like IEEE 802.16m (WiMax). A new frontier for wireless communications for smart grids, especially for metering applications, is represented by Wireless Sensor Networks (WSN) within the framework of Internet of Things (IoT) [108] and Machine-to-Machine (M2M) communications [109].

Low-cost frequency shift keying (FSK) radios in the white-space spectrum can also represent a valid option for wireless data networks, as declared by the National Broadband Plan, the Federal Communications Commission (FCC). White spaces are open, unused TV broadcast channels in the VHF and UHF regions, made available by the recent transition from analog to digital TV. White-space radios essentially have a longer range and greater link reliability, even without a line-of-sight (LOS) path if compared with Wi-Fi, ZigBee, and other radios operating in the microwave bands [110].

7.2. *Wired communication systems*

Depending on the desired coverage area, various technologies can be used for wired communication. Power line communications (PLCs) may be adopted for HANs and NANs in order to cover local/micro SG portions (up to hundreds of meters). Fiber optic communications may instead be implemented for WAN (tens of kilometers, and more).

As micro SGs represent the basic building blocks, where most of the intelligence is employed, the local aspects of SG wired communications are deepened here, where the commonly accepted wired solution is PLC offering a natural communication channel for SGs and guaranteeing robustness and reliability, with no need of new infrastructures.

A comprehensive overview on the characteristics of PLC and on their role in the SG context can be found in [106,111–115]. Two main families of PLC technologies exist which we can identify as narrowband or broadband.

Narrowband PLCs, characterized by a limited bandwidth at low frequencies, with an attenuation of very few dBs per kilometer, limited bit rate and long packet dimension (comparable to the 20 ms electrical cycle), are suitable for centralized, low speed, high latency applications, such as data gathering, monitor and control of the household power consumption, load scheduling and DR. Consequently, most recent technological solutions, mainly based on orthogonal frequency division multiplexing (OFDM) for an efficient usage of frequency resources even with a frequency selective channel, offer centralized medium access control (MAC) structures with a concentrator at the root of the topology tree providing connectivity to nodes and sub-networks [105]. In order to guarantee a quality of service (QoS) level that is adequate for SG control, robust coding techniques are required and consequently the available rate cannot exceed 50 kbps at the physical layer.

Broadband PLCs are mainly suitable for in-home communications (indoor micro SGs) as they run on higher frequencies (typically 2–30 MHz) which guarantee higher bit rates but much lower coverage of up to few hundreds of meters, mainly due to the much more severe attenuation in this frequency range. However, by limiting the available bit rate (to 3.8 Mbps) and setting modulation parameters to robust mode choices, these protocols can be also used for outdoor micro SGs. The broadband solutions, characterized by short packet durations (much less shorter than the 20 ms electrical cycle), are particularly appropriate for two-way communication and distributed control in order to guarantee optimal operation of real-time algorithms [105].

Channel and topology models, constituting the basis for any upper layer optimization activity, represent aspects of active research in PLCs. In particular, researches on statistical topology models are of specific interest to both communications and power systems since very few researches exist [116,117].

8. Examples of smart grid infrastructures for demand response

In this section two examples of smart grid infrastructures for DR are described: the infrastructure required to implement a DRP and that for plug-in electric vehicles (EVs).

8.1. Demand response provider implementation

An efficient infrastructure to implement a DRP practically is an EMS in a SG infrastructure as shown in Fig. 7. The main components of the smart grid are [79–82]: EMS and DRP, SCADA, RTUs, AMI, state estimation algorithms (SEAs), generation and load forecast system (GLFS). Monitoring, control and optimization functions of the SG are carried out by the EMS [79–82]. AMI and RTUs provide the measurement data that are transmitted by the SCADA system to the EMS that, by means of SEAs and GLFS, decides the required actions for the optimal management of the SG. The AMI communications infrastructure supports continuous interaction between the utility, the consumer and the controllable electrical load. Collection networks for meter data, NANs, may be any one of wireless, cellular, PLC, etc. The utility WANs may similarly be private or public Wi-Fi, T1, WiMAX, fiber or cellular networks.

8.2. Demand response infrastructure for plug-in electric vehicles

In a smart charging approach [48,105], EVs may behave as a load to the distribution grid, a supplier of electricity to the grid or an energy storage device. Thanks to the smart grid enabling technologies, utilities can manage EV charging time and rates, gather EV-detailed meter data and, therefore, implement DR programs. EV charge management should be integrated in DSM operation by utilities. The integration of EV supply equipment (EVSE) with distribution automation (DA) provides utilities better flexibility and reliability in managing and delivering electrical energy. It also supports utilities in reducing peak demand impacts and preserving power quality in presence of RES, by optimizing and coordinating intermittent RES with EV charging.

Moreover, the high plugged-in time, of about 10–15 h a day, during which EVs are estimated to be available for charging or discharging the battery, makes them also ideal for providing ancillary services, such as frequency regulation, while meeting the charging constraints specified by the driver [48]. An aggregator can centrally control smart charging choice of each group of EVs or a charging strategy can be decided in collaboration with individual EVs in a group.

Smart charging should be effectively supported by robust, reliable and secure connectivity to the EVSE charger. AMI infrastructure is, therefore, required to integrate EVs in DR programs. By enabling a two-way communication and providing customers and utilities with real-time data, AMI allows customers scheduling charging in order to minimize total costs. Simultaneously, utilities may also envisage local reliability issues by following and reporting EV charging usage.

Utilities should prefer NANs to HANs in order to communicate with the EVSE as NANs offer better range and propagation characteristics, ensuring multiple communications paths for higher reliability, peer-to-peer communications between the EVSE and other smart grid devices, robust device monitoring and remote upgrade capabilities. Most EVs are linked to the Internet through Wi-Fi, ZigBee communication network or cellular network. By using the Internet-enabled communication, the aggregator may collect EVs into different groups of variable sizes and handle each group as a dispatchable load to the grid [48].

9. Lessons learnt from industrial case studies and research projects

Nowadays, several smart grid pilots including DR programs and providing a variety of smart grid applications and approaches are under development in all over the world. Most smart grid-related activities are concentrated on smart meters and AMI, regulations promoting net metering, data privacy issues, opt-out policies, and DG programs. They involve various technology types, pricing programs, and funding mechanisms.

9.1. Smart grid pilots and programs

Some case studies related to smart grid pilots and programs in the U.S. with quantitative results and metrics are available in [118]. Successful programs evidenced that the combined use of smart grid technologies with DR programs allows utilities realizing significant economic savings thanks to peak demand flattening that avoids the need for more generation capacity and reduces peak power costs. Higher peak load reductions can be achieved by correctly identifying the subset of facility types that are most appropriate to benefit from DR. Due to cost savings from reduced energy consumption and power quality enhancements, consumers also benefit from these programs.

Dynamic pricing and demand bidding, that require sophisticated control technology, are usually adopted by large customers; however, automated technologies greatly enhance also the responsiveness of small and medium retail customers. In order to ensure performance and cost effectiveness, the implementation of automated response technology for small customers requires instead careful marketing and consumer targeting. Conversely, interruptible load response, targeted at large commercial and industrial customers, is usually used for emergency programs that can be

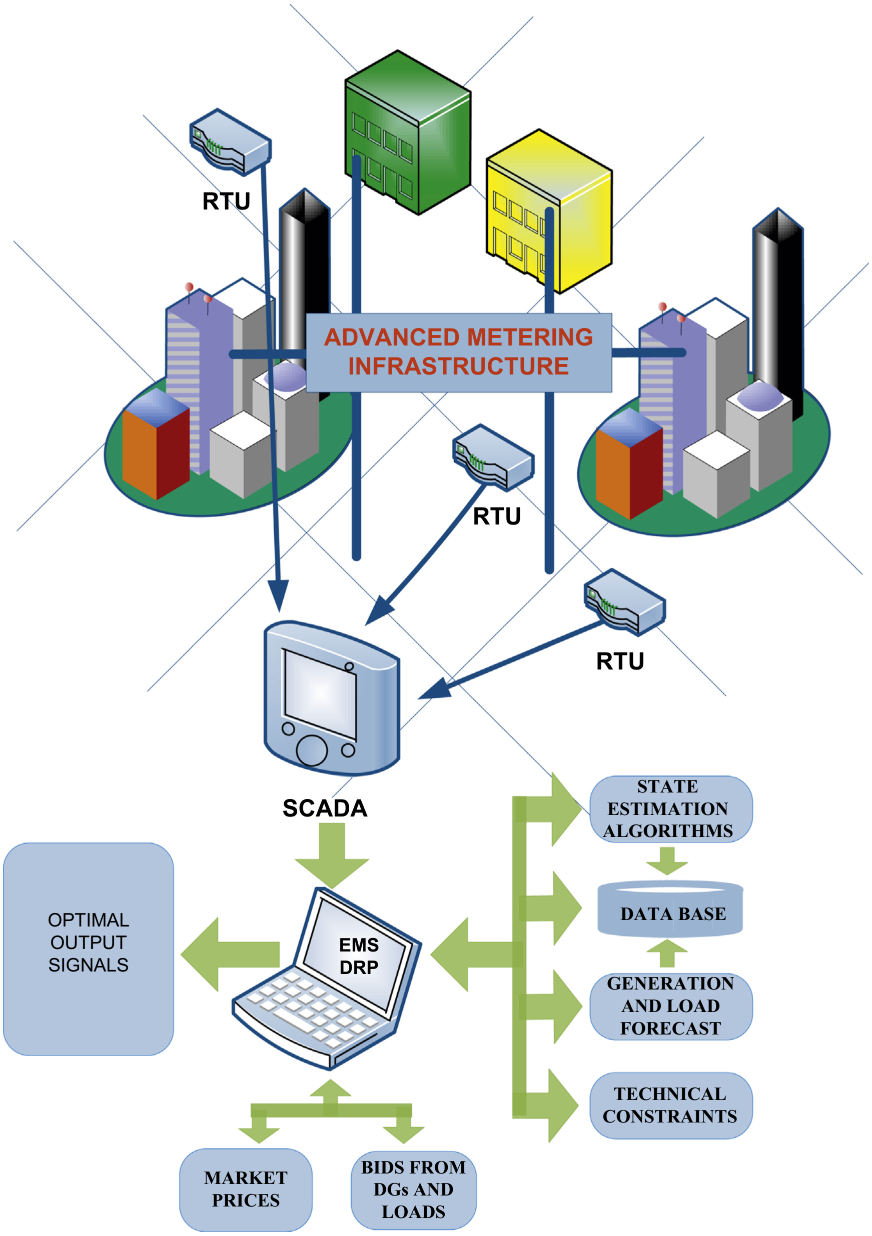

Fig. 7. Energy management system in the smart grid infrastructure [85].

costly even if utilities pay incentives for participation as limited to few hours over the year [97,119].

It is worth noting that, even if success in creating DR as a feasible energy resource is increasing during last years, utilities continue to fight with both extending and retaining customer employment, as well as encouraging participation. Lack of interoperability between different smart grid elements and technological immaturity of certain smart grid components represent the most common technical obstacle reported. On the other end, investments in DR technologies may be limited by the uncertainty over the sharing of costs and benefits among different stakeholders and by the uncertainty related to roles and responsibilities of players [97,119].

9.2. *Industrial case studies of DR applications*

Some industrial case studies of DR applications are presented in [119] and briefly described in the following.

Alcoa, the major consumer and supplier of electricity in the US, by participating in the Midwest ISO (MISO) wholesale market, provides regulation as an ancillary service [120,121]. In order to participate to ancillary services market through control of smelter loads, Alcoa installed an EMS, smelter potline load control system (LCPD), and metering and monitoring systems. Three redundant communication channels guarantee the communication between MISO and the EMS of MW set-point instructions that are converted by the EMS into a potline sequence of operations and sent to the LCPD that performs the established sequences. Loads are monitored by telemetry equipment, storing loads every 2 s and cycling the aluminum smelting potline and controlling the voltage of the potlines represent the mostly used DR strategies. Revenues from DR participation allowed paying back the cost of the system (of around $700,000) in 4 months.

Another industrial application is related to Amy's Kitchen in California with a processing plant producing packaged vegetarian meals. In 2008, this facility participated in PG&E's Automated DR (Auto-DR) program based on open automated demand response (OpenADR) [122] that is an information exchange model established to communicate price and reliability information to large commercial and industrial facilities. Prices, reliability information, or load instructions are translated by the automation systems in pre-programmed response sequences.

The facility includes several large cool rooms, freezers, blast freezers and a spiral freezer and multiple support loads, such as HVAC and lighting loads. The facility is notified by the utility a day-ahead using OpenADR about the DR event period. The signals are received by the facility EMS that is associated to an OpenADR client. When the DR event starts the EMS triggers pre-programmed DR strategies such as shutting off some freezers and the battery chargers and raising the set-points on other freezers and cool rooms.

Significant load reduction and DR programs are also promoted in New York State by NYSERDA and NYISO. On request from NYISO, Lafarge Building Materials, a cement processing plant [123], can shed 22 MW of optional load by shutting down its rock crushing equipment, while the plant can continue its production thanks to the facility storage capacity. The payment for load curtailment is made in agreement with NYSERDA's Peak Load Reduction Program. As Lafarge also participates in NYISO's Day Ahead DR Program, it may also sell the unused energy into the market whereas maintenance on equipment can be programmed at times when grid prices are low. Even if the implementation of these programs required 26 miles of fiber optic Ethernet cable, Internet connectivity for pricing information and EMS functionality, it allowed around $2 million of revenues.

10. Conclusion

DR will play a major role in the SG implementations and will allow benefits on system operation and expansion and on market efficiency. It can be employed for overall load reductions in response to peak power concerns and for ancillary services for frequency regulation with faster scale response times (up to 4-s response times).

Lessons learnt from industrial case studies and research projects evidenced that advanced DR programs and innovative enabling technologies are required for such applications and to support the coordination of DR in smart grids. Enabling technologies, such as smart meters, AMI, home energy controllers, EMS, wired and wireless communication systems are required as evidenced by real industrial case studies and research projects.

The integration of storage devices, distributed generation and on-site RES in automated DR brings additional flexibility and complexity that should be managed with innovative technologies and methods.

Important areas for research that require to be further investigated in this field include measurement and settlement processes, developments in integrated electronic circuits, optimization and control systems, information and communications technologies. Considering that the smart metering and the charging infrastructures should be regulated assets of public utility, further researches are required to discuss regulatory and policy recommendations in order to ensure technical functioning and non-discriminatory physical access to all parties and precise rules, defining roles and responsibilities of all players and assuring fair sharing of costs and benefits among all stakeholders.

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